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Beerling

(54) LIQUID METAL SWITCH EMPLOYING ELECTROWETTING FOR ACTUATION AND ARCHITECTURES FOR IMPLEMENTING SAME

(76) Inventor: **Timothy Beerling**, San Francisco, CA (US)

Correspondence Address:
AGILENT TECHNOLOGIES, INC.
Intellectual Property Administration
Legal Department, DL429
P.O. Box 7599
Loveland, CO 80537-0599 (US)

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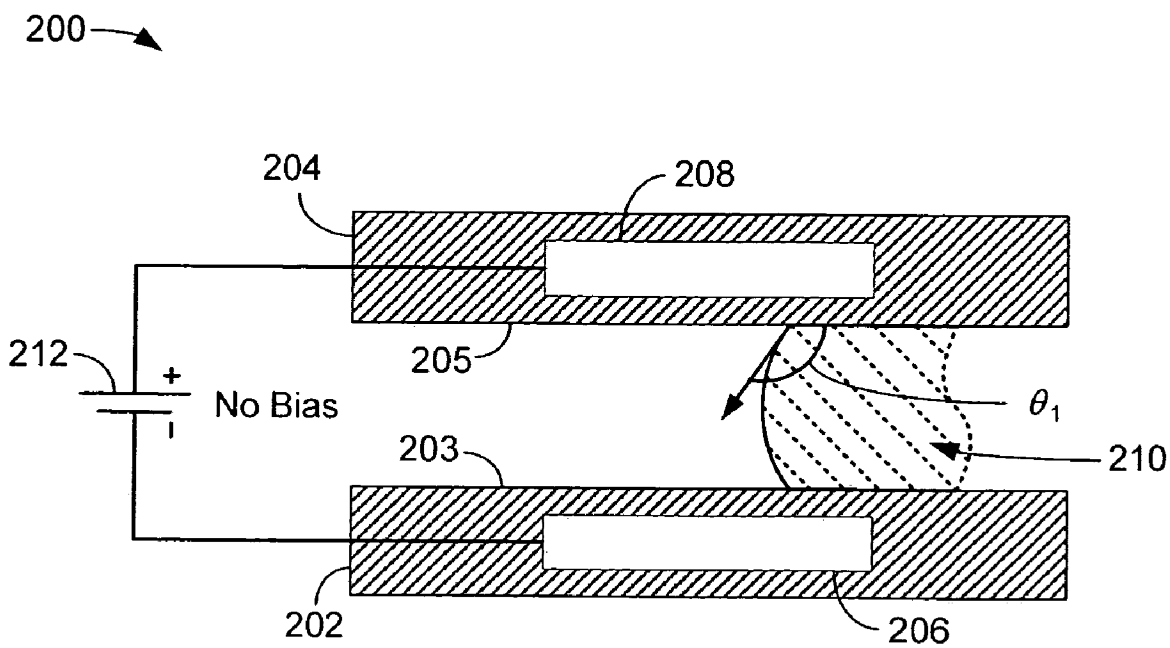
(52) **U.S. Cl.** **200/182**

(57) **ABSTRACT**

An electronic switch comprises a substrate having a surface and an embedded electrode, a droplet of conductive liquid located over the embedded electrode, and a power source configured to create an electric circuit including the droplet of conductive liquid. The surface comprises a feature that determines a contact angle between the surface and the droplet.



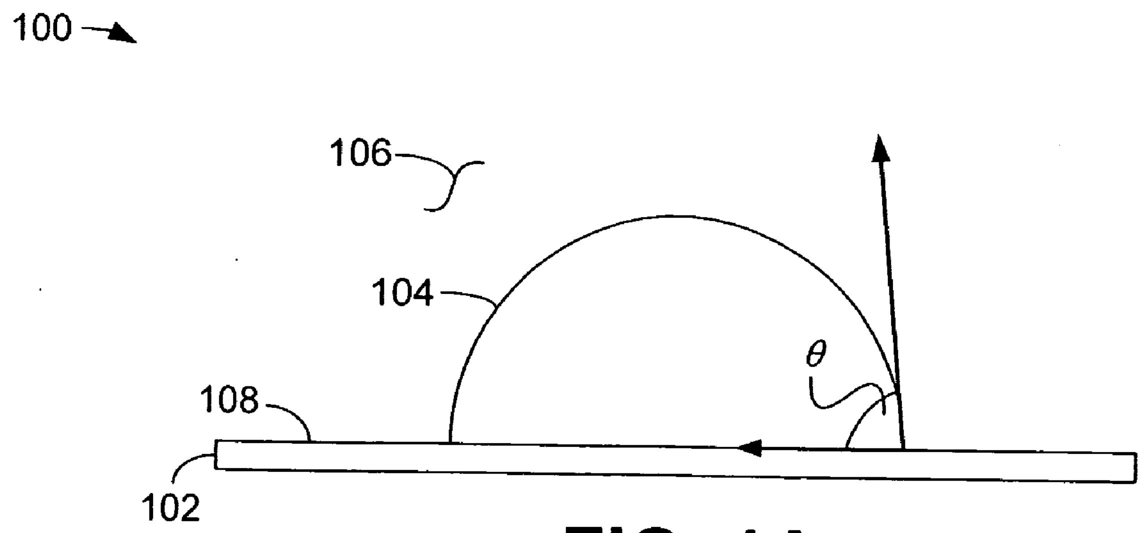


FIG. 1A

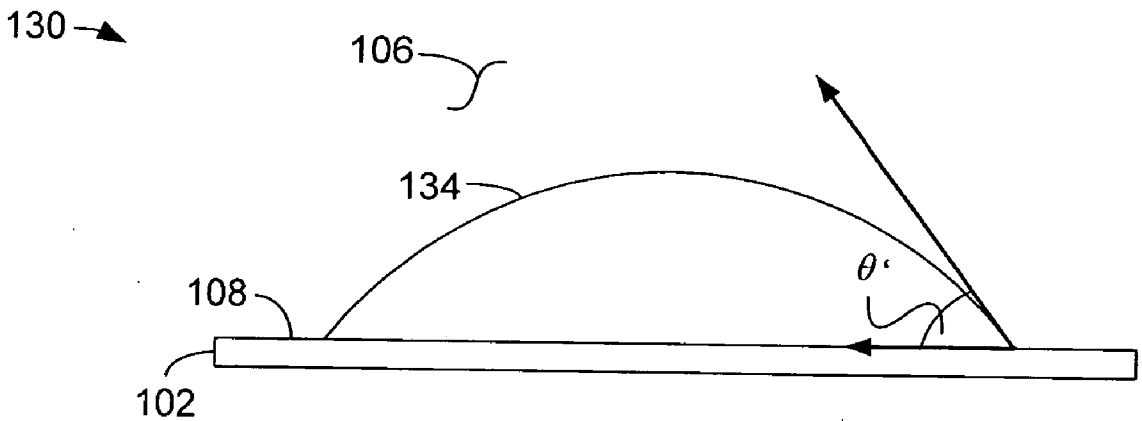


FIG. 1B

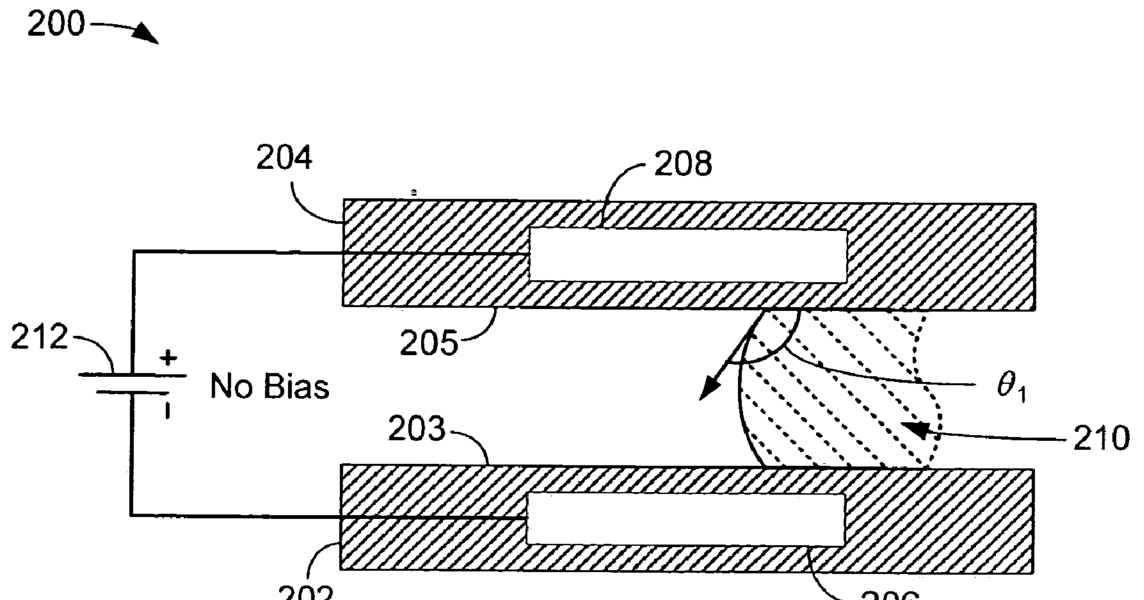

200
204
208
212
+
No Bias
205
θ_1
203
210
202
206

FIG. 2A

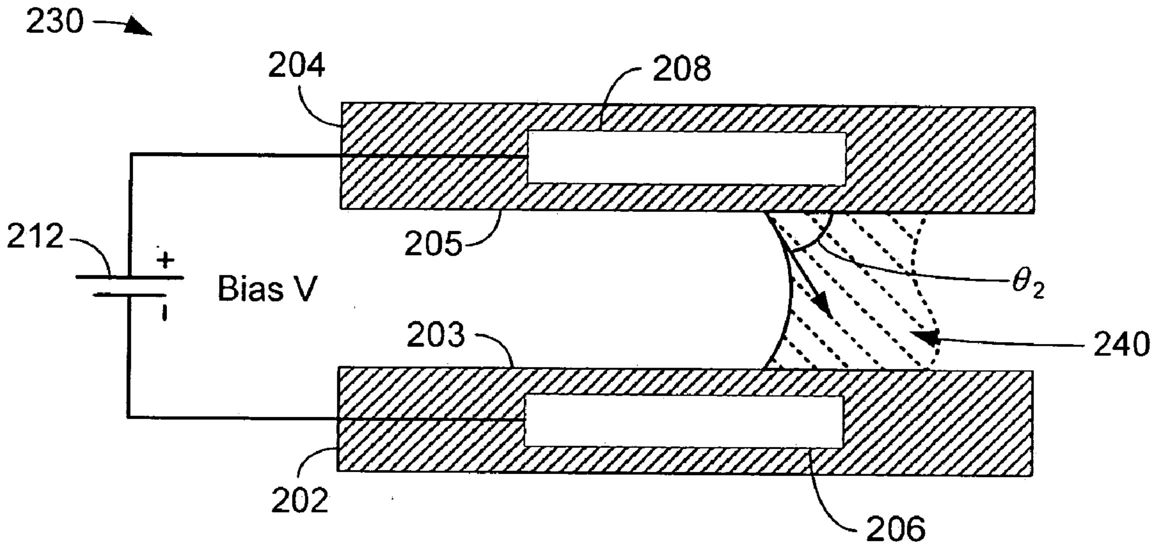

230
204
208
212
+
Bias V
205
θ_2
203
240
202
206

FIG. 2B

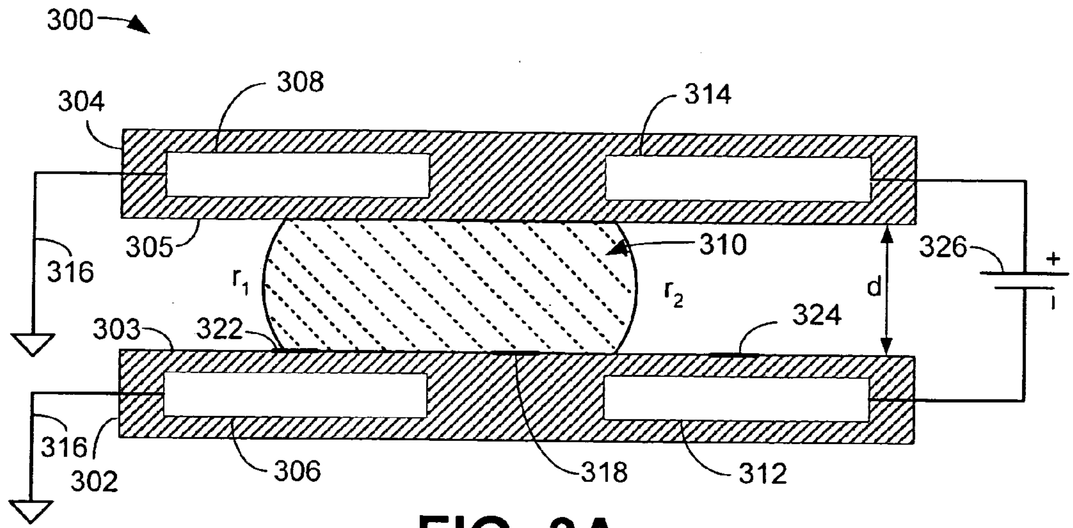


FIG. 3A

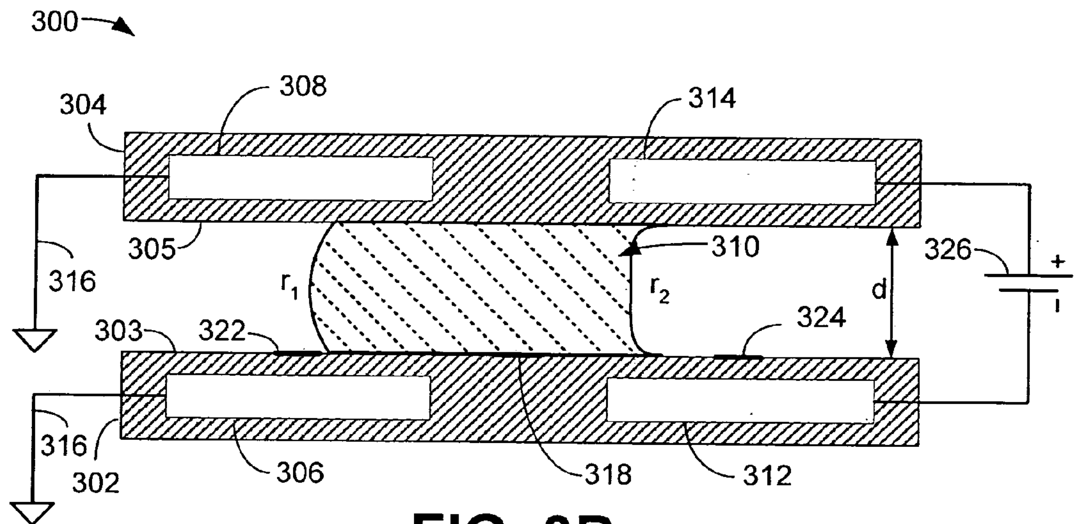


FIG. 3B

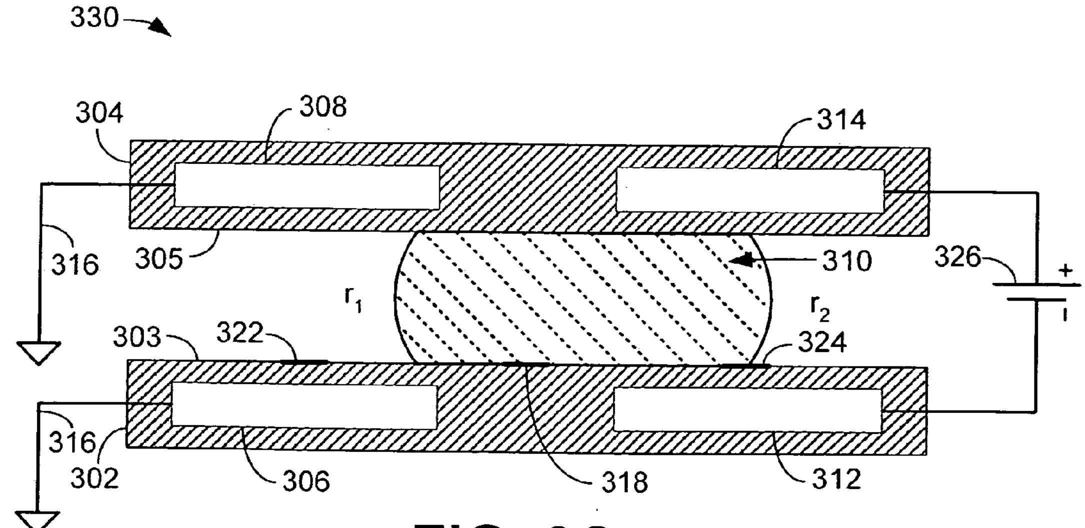


FIG. 3C

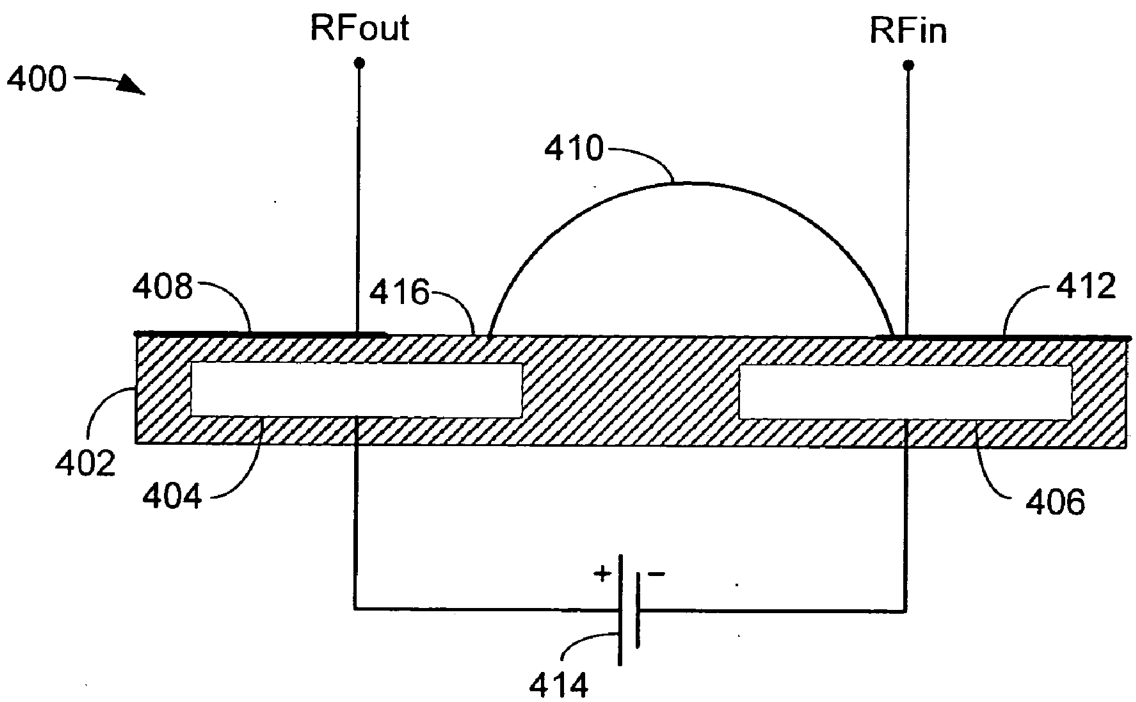

RFout
RFin
400
410
408
416
412
402
404
406
+
-
414

FIG. 4A

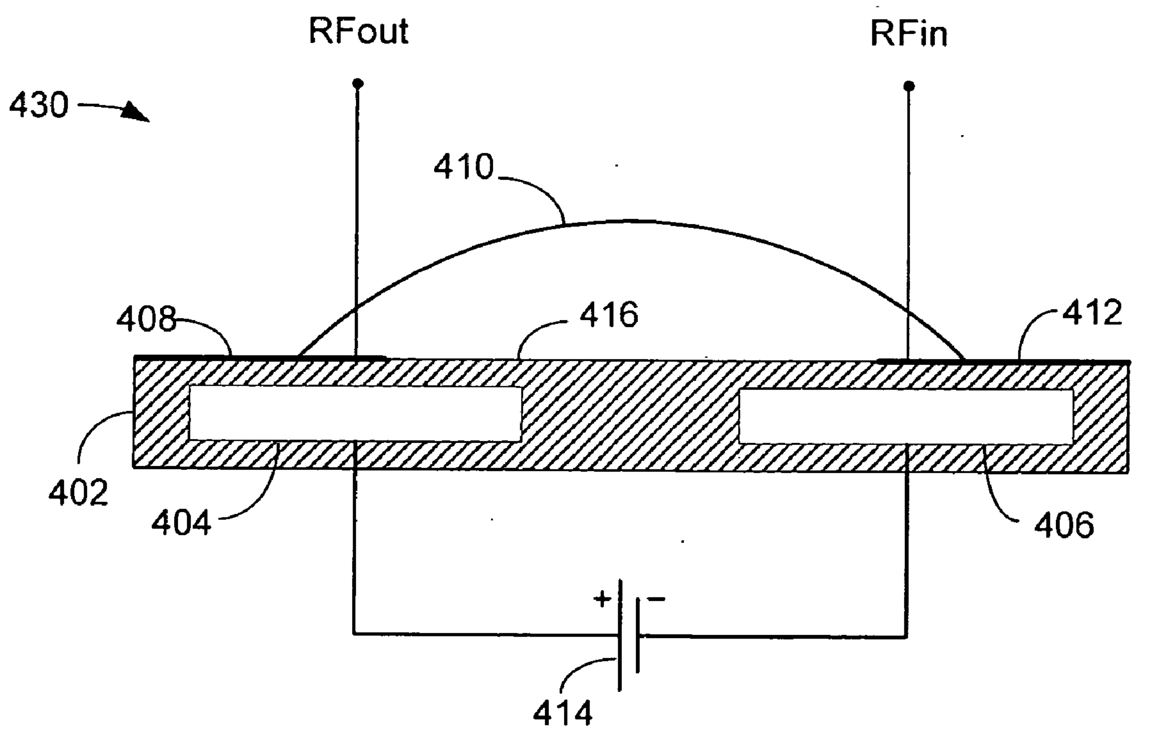

RFout
RFin
430
410
408
416
412
402
404
406
+
-
414

FIG. 4B

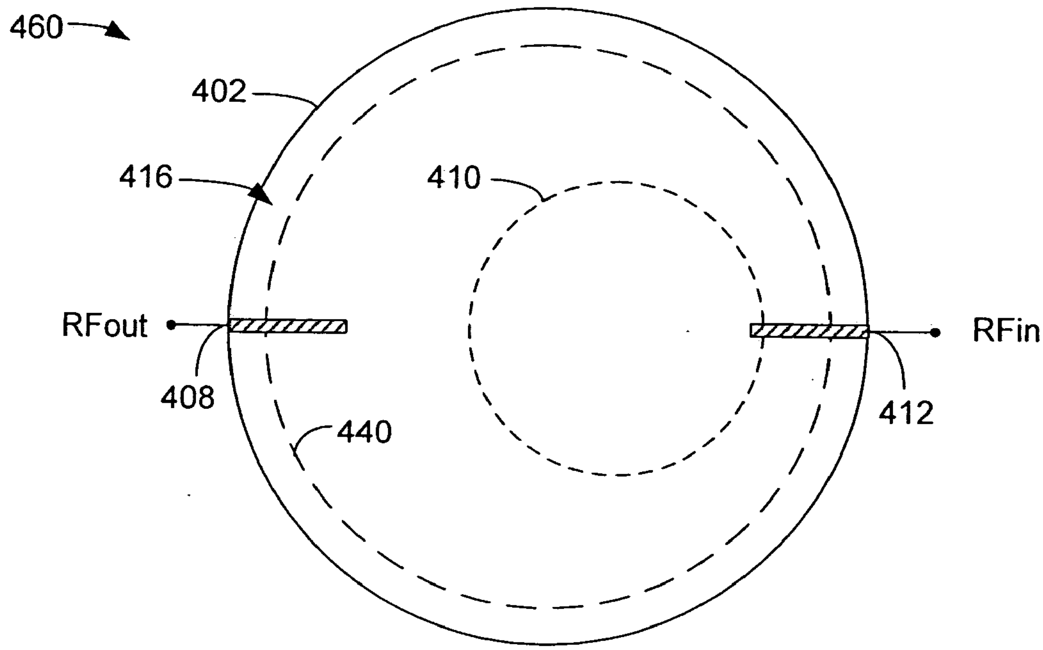


FIG. 4C

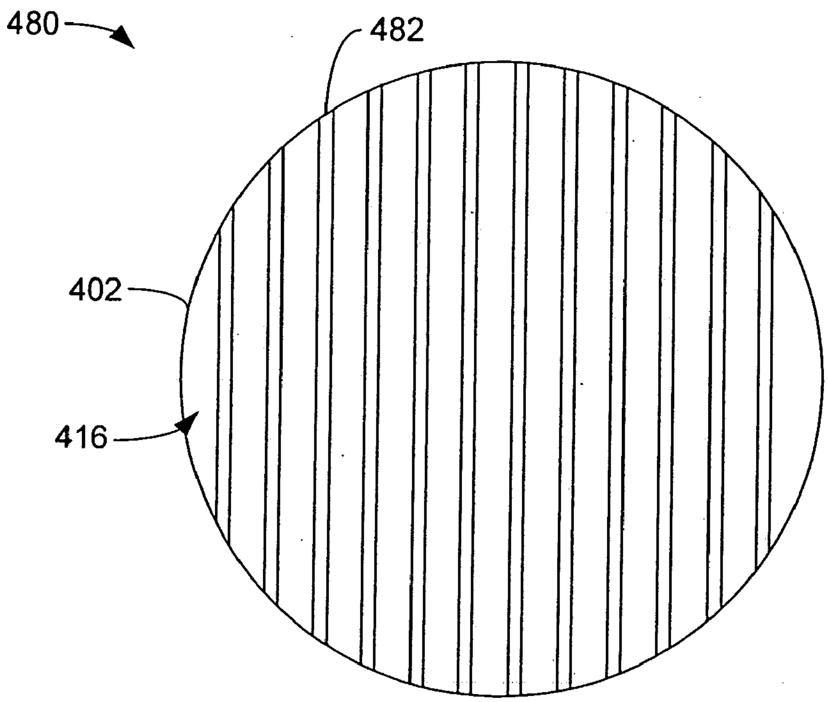


FIG. 4D

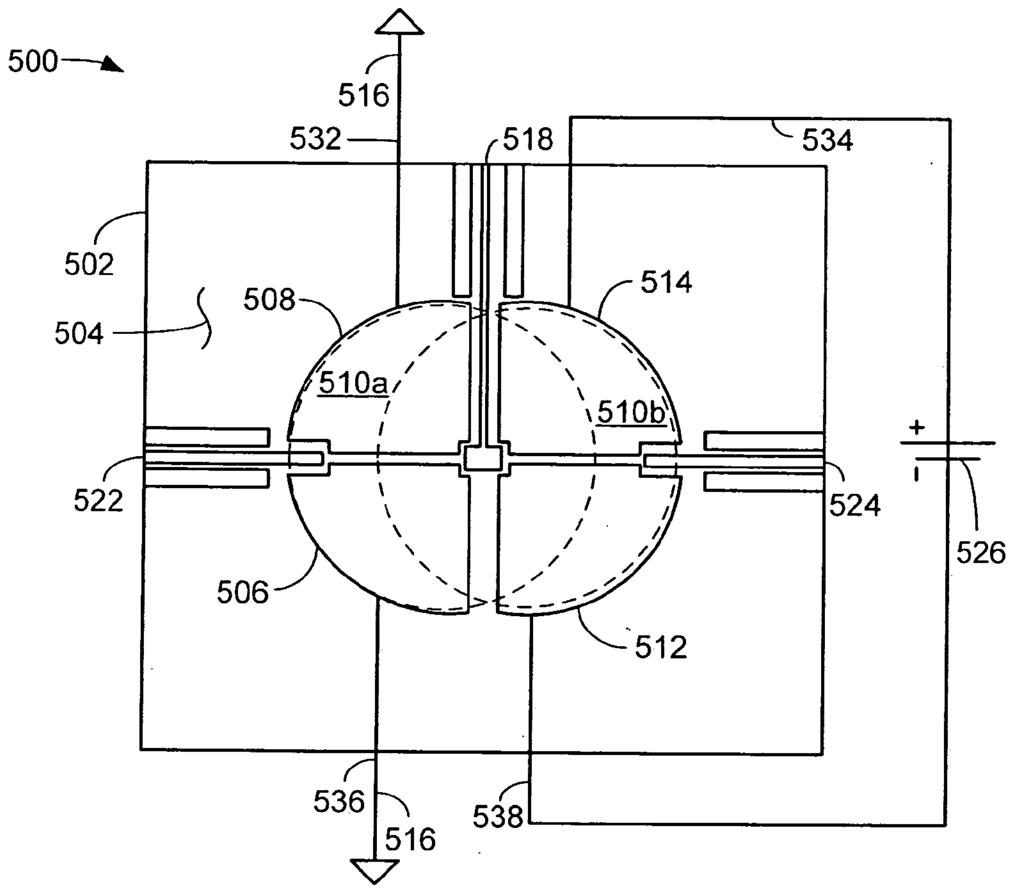

500
516
532
518
534
502
504
508
514
510a
510b
522
524
526
506
512
536
516
538

FIG. 5A

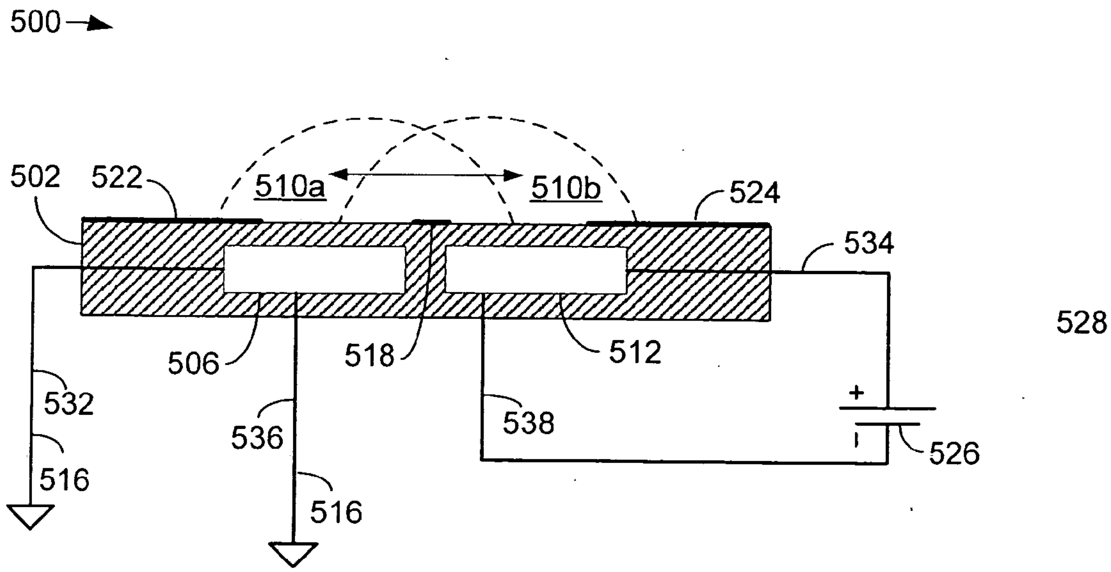

500
502
522
510a
510b
524
534
528
506
518
512
532
516
536
538
526
516

FIG. 5B

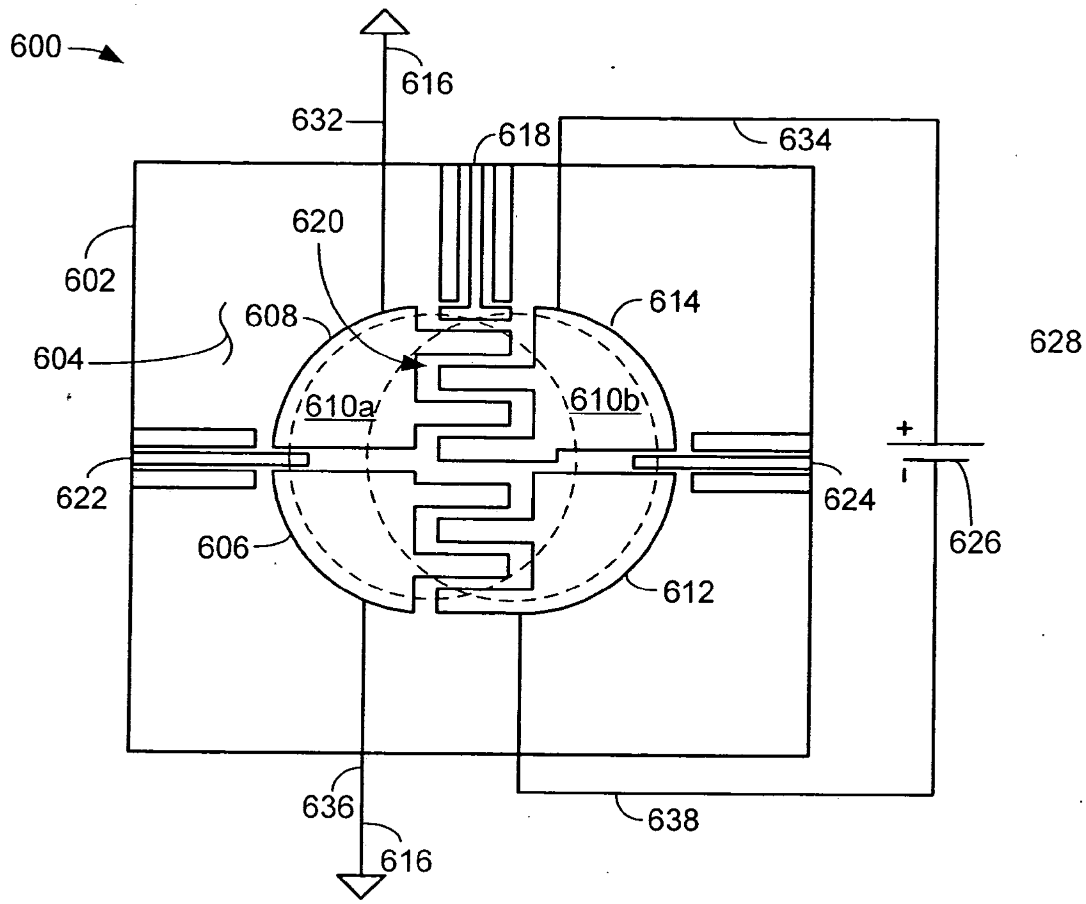

600
616
632
618
634
602
620
608
614
604
610a
610b
628
622
624
606
626
612
636
638
616

FIG. 6A

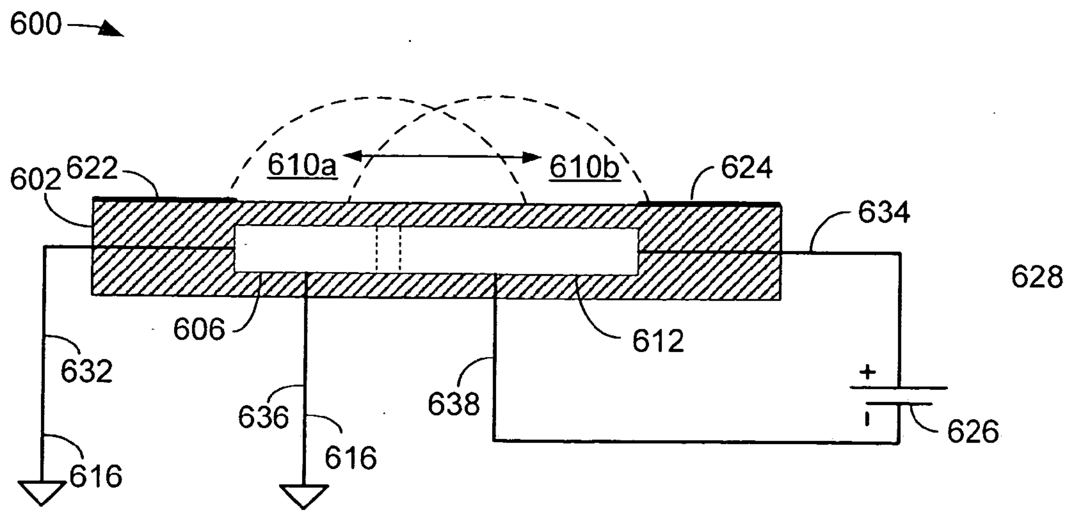

600
602
622
610a
610b
624
634
628
606
612
632
636
638
626
616
616

FIG. 6B

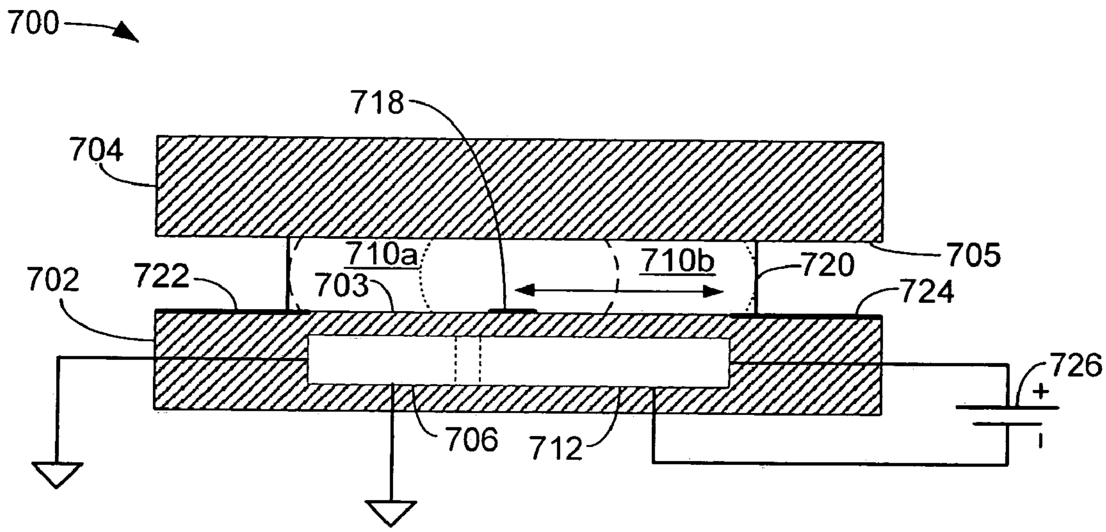

700
718
704
705
710a
710b
720
702
722
703
724
726
+
706
712

FIG. 7

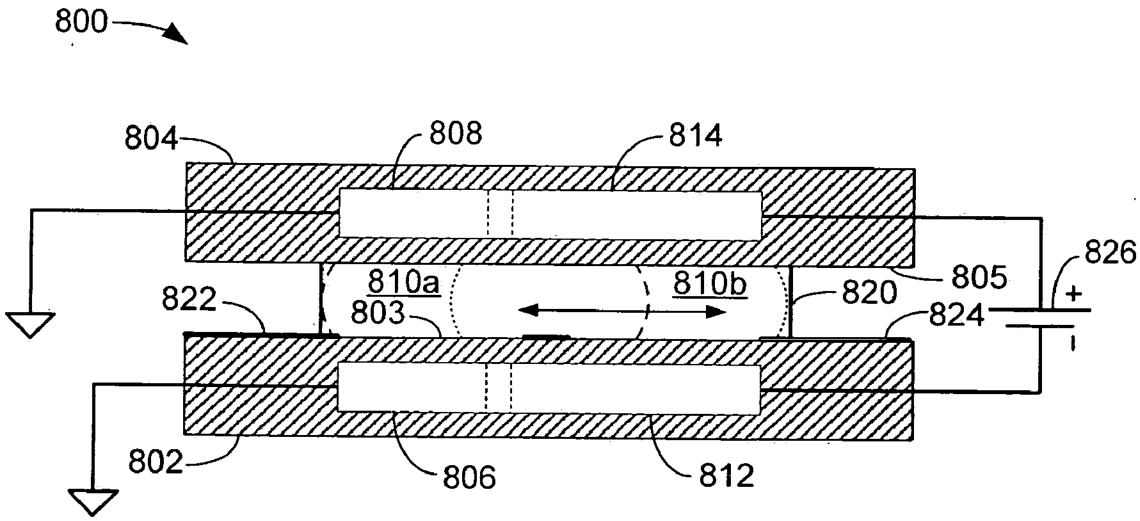

800
804
808
814
805
826
810a
810b
820
822
803
824
+
802
806
812

FIG. 8

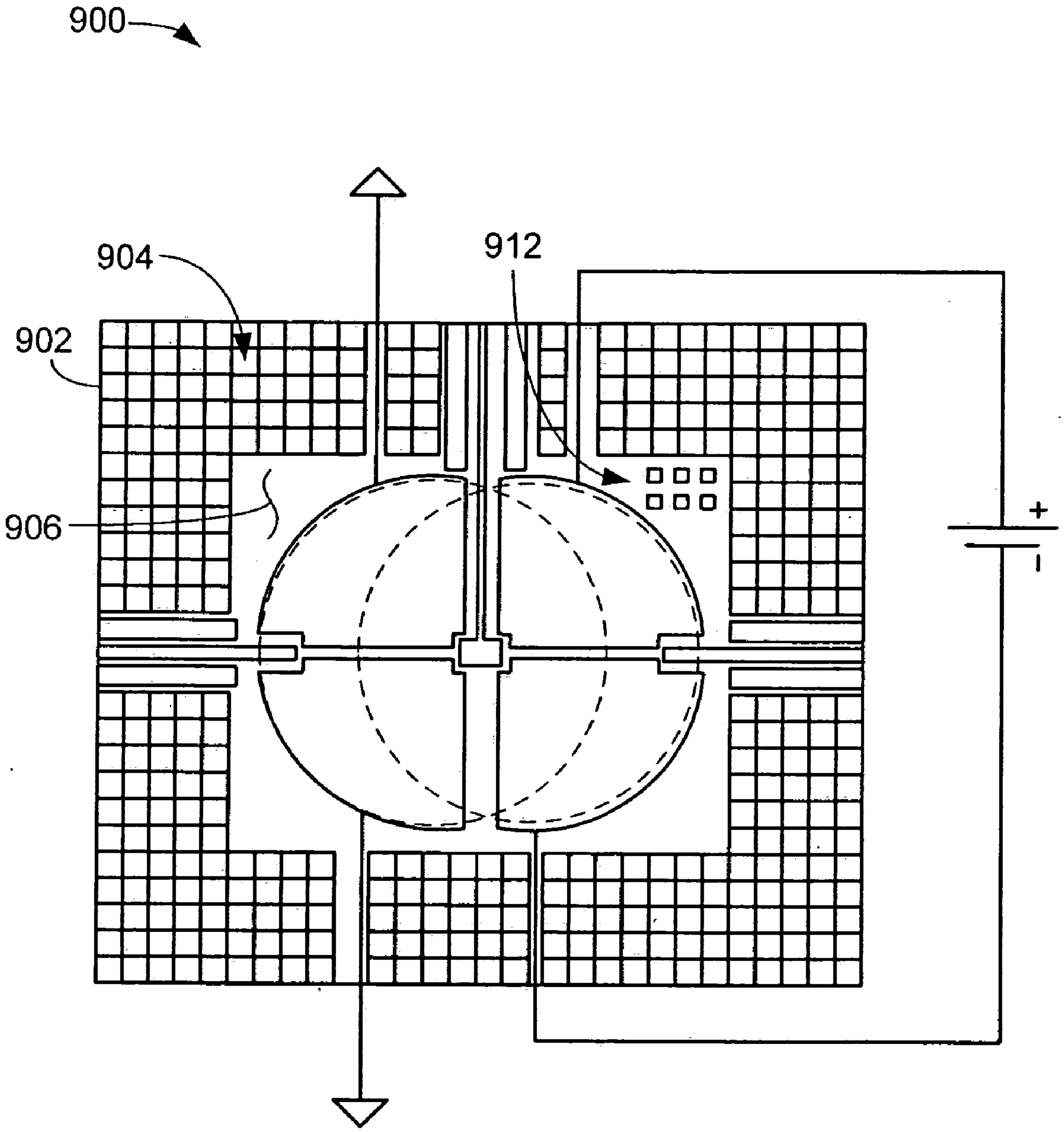


FIG. 9

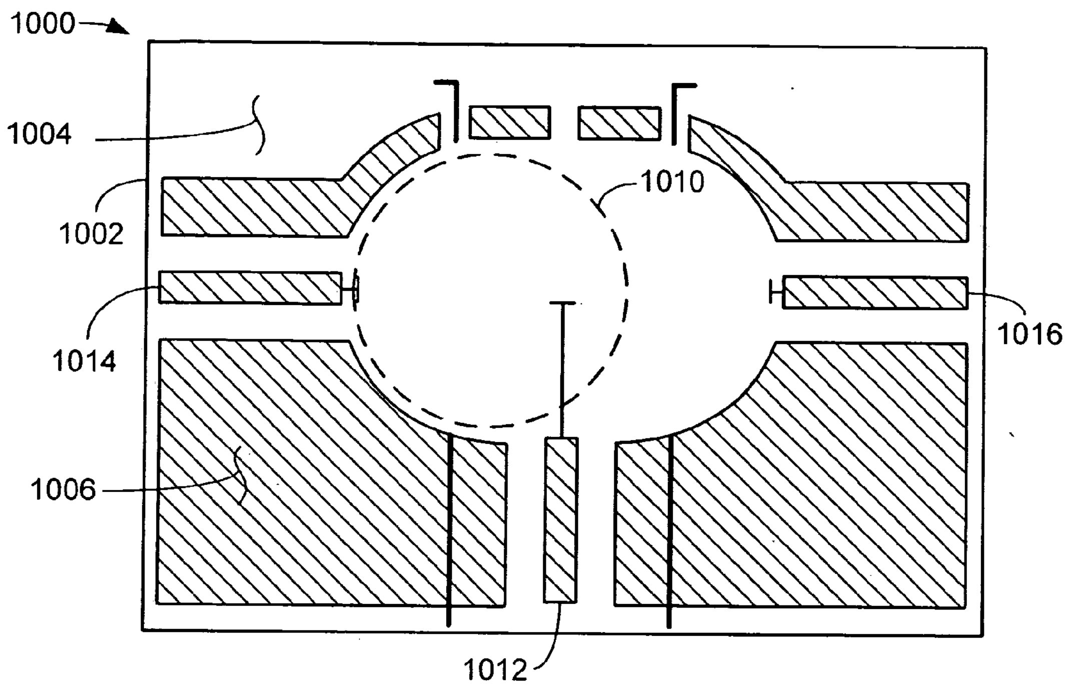

1000
1004
1002
1010
1014
1016
1006
1012

FIG. 10

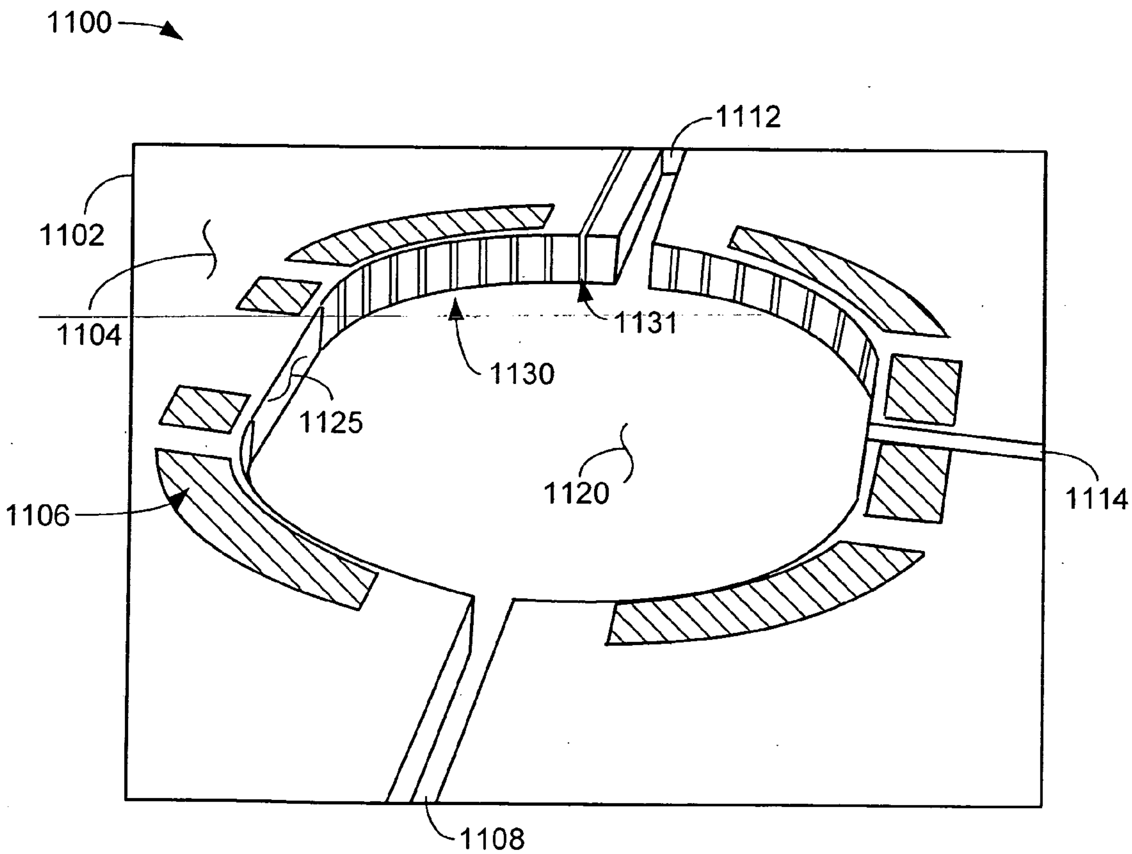

1100
1112
1102
1104
1131
1130
1125
1120
1114
1106
1108

FIG. 11

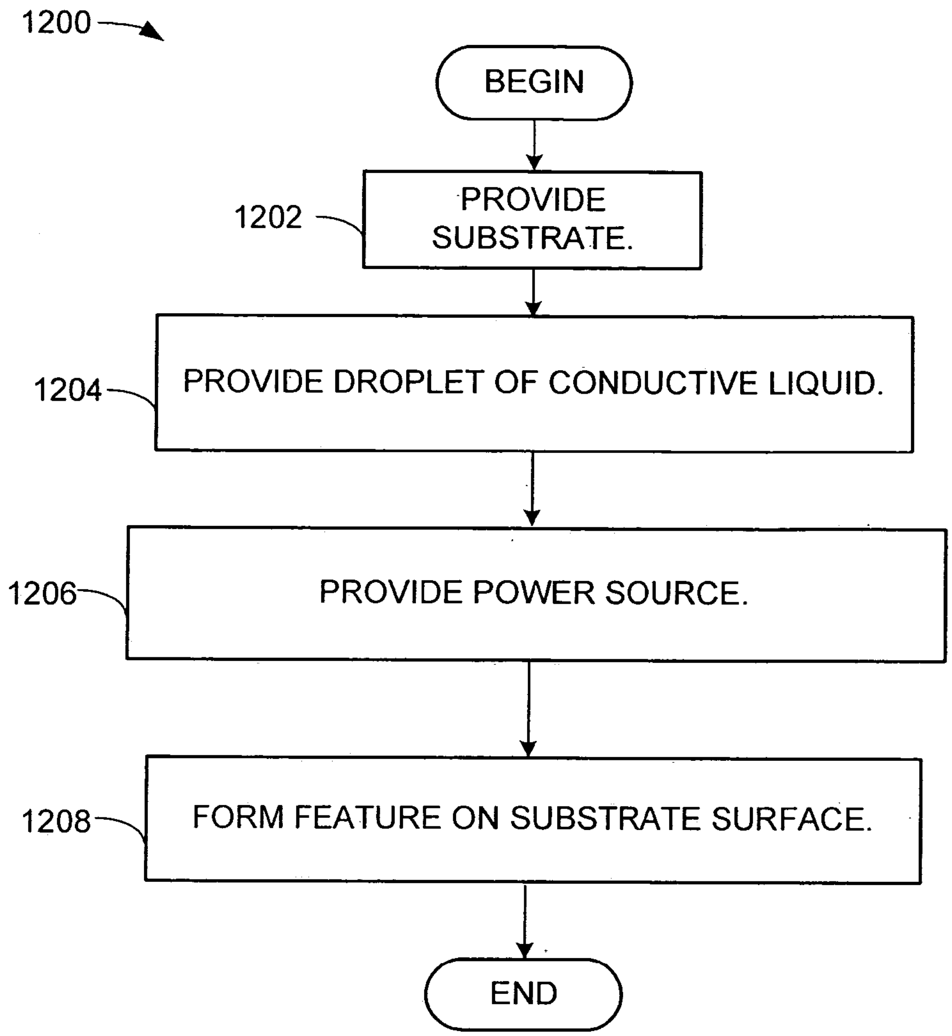

1200
BEGIN
1202
PROVIDE SUBSTRATE.
1204
PROVIDE DROPLET OF CONDUCTIVE LIQUID.
1206
PROVIDE POWER SOURCE.
1208
FORM FEATURE ON SUBSTRATE SURFACE.
END

FIG. 12

LIQUID METAL SWITCH EMPLOYING ELECTROWETTING FOR ACTUATION AND ARCHITECTURES FOR IMPLEMENTING SAME

BACKGROUND OF THE INVENTION

[0001] Many different technologies have been developed for fabricating switches and relays for low frequency and high frequency switching applications. Many of these technologies rely on solid, mechanical contacts that are alternatively actuated from one position to another to make and break electrical contact. Unfortunately, mechanical switches that rely on solid-solid contact are prone to wear and are subject to a condition known as "fretting." Fretting refers to erosion that occurs at the points of contact on surfaces. Fretting of the contacts is likely to occur under load and in the presence of repeated relative surface motion. Fretting typicaly manifests as pits or grooves on the contact surfaces and results in the formation of debris that may lead to shorting of the switch or relay.

[0002] To minimize mechanical damage imparted to switch and relay contacts, switches and relays have been fabricated using liquid metals to wet the movable mechanical structures to prevent solid to solid contact. Unfortunately, as switches and relays employing movable mechanical structures for actuation are scaled to sub-millimeter sizes, challenges in fabrication, reliability and operation begin to appear. Micromachining fabrication processes exist to build micro-scale liquid metal switches and relays that use the liquid metal to wet the movable mechanical structures, but devices that employ mechanical moving parts can be overly-complicated, thus reducing the yield of devices fabricated using these technologies. Therefore, a switch with no mechanical moving parts may be more desirable.

SUMMARY OF THE INVENTION

[0003] In accordance with the invention an electronic switch is provided comprising a substrate having a surface and an embedded electrode, a droplet of conductive liquid located over the embedded electrode; and a power source configured to create a capacitive circuit including the droplet of conductive liquid. The surface comprises a feature that determines an initial contact angle between the surface and the droplet.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] The invention can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the present invention. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

[0005] **FIG. 1A** is a schematic diagram illustrating a system including a droplet of conductive liquid residing on a solid surface.

[0006] **FIG. 1B** is a schematic diagram illustrating the system of **FIG. 1A** having a different contact angle.

[0007] **FIG. 2A** is a schematic diagram illustrating one manner in which electrowetting can alter the contact angle between a droplet of conductive liquid and a surface that it contacts.

[0008] **FIG. 2B** is a schematic diagram illustrating the system of **FIG. 2A** under an electrical bias.

[0009] **FIG. 3A** is a schematic diagram illustrating an embodiment of an electrical switch employing a conductive liquid droplet.

[0010] **FIG. 3B** is a schematic diagram illustrating the movement imparted to a droplet of conductive liquid as a result of the change in contact angle due to electrowetting.

[0011] **FIG. 3C** is a schematic diagram illustrating the switch of **FIG. 3A** after the application of an electrical potential.

[0012] **FIG. 4A** is a schematic diagram illustrating the cross-section of a switch according to a first embodiment of the invention.

[0013] **FIG. 4B** is a schematic diagram illustrating the switch of **FIG. 4A** under an electrical bias.

[0014] **FIG. 4C** is a plan view illustrating the switch shown in **FIGS. 4A and 4B**.

[0015] **FIG. 4D** is a plan view illustrating the surface of the dielectric including a feature that alters the wettability of the surface with respect to the droplet.

[0016] **FIG. 5A** is a plan view illustrating a second embodiment of a switch according to the invention.

[0017] **FIG. 5B** is a cross-sectional view illustrating the switch of **FIG. 5A**.

[0018] **FIG. 6A** is an alternative embodiment of the switch shown in **FIG. 5A**.

[0019] **FIG. 6B** is a cross-sectional view illustrating the switch of **FIG. 6A**.

[0020] **FIG. 7** is a schematic diagram illustrating another alternative embodiment of a switch according to the invention.

[0021] **FIG. 8** is a schematic diagram illustrating an alternative embodiment of the switch shown in **FIG. 7**.

[0022] **FIG. 9** is a schematic diagram illustrating surface texturing that can be applied to the switch of **FIGS. 5A and 5B**.

[0023] **FIG. 10** is a schematic diagram illustrating an exemplary dielectric substrate that may form the lower surface, or floor, of a switch described above.

[0024] **FIG. 11** is a perspective view illustrating a cap that forms the roof and microfluidic chamber of a switch of **FIG. 7, 8** or **9**.

[0025] **FIG. 12** is a flowchart describing a method of forming a switch according to an embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0026] The switch structures described below can be used in any application where it is desirable to provide fast, reliable switching. While described below as switching a radio frequency (RF) signal, the architectures can be used for other switching applications.

[0027] **FIG. 1A** is a schematic diagram illustrating a system **100** including a droplet of conductive liquid residing on a solid surface. The droplet **104** can be, for example, mercury or a gallium alloy, and resides on a surface **108** of a solid **102**. A contact angle, also referred to as a wetting angle, is formed where the droplet **104** meets the surface

108. The contact angle is indicated as θ and is measured at the point at which the surface **108**, liquid **104** and gas **106** meet. The gas **106** can be, in this example, air, or another gas that forms the atmosphere surrounding the droplet **104**. A high contact angle, as shown in **FIG. 1A**, is formed when the droplet **104** contacts a surface **108** that is referred to as relatively non-wetting, or less wettable. The wettability is generally a function of the material of the surface **108** and the material from which the droplet **104** is formed, and is specifically related to the surface tension of the liquid.

[0028] **FIG. 1B** is a schematic diagram **130** illustrating the system **100** of **FIG. 1A** having a different contact angle. In **FIG. 1B**, the droplet **134** is more wettable with respect to the surface **108** than the droplet **104** with respect to the surface **108**, and therefore forms a lower contact angle, referred to as θ'. As shown in **FIG. 1B**, the droplet **134** is flatter and has a lower profile than the droplet **104** of **FIG. 1A**.

[0029] The concept of electrowetting, which is defined as a change in contact angle with the application of an electrical potential, relies on the ability to electrically alter the contact angle that a conductive liquid forms with respect to a surface with which the conductive liquid is in contact. In general, the contact angle between a conductive liquid and a surface with which it is in contact ranges between 0° and 180°.

[0030] **FIG. 2A** is a schematic diagram **200** illustrating one manner in which electrowetting can alter the contact angle between a droplet of conductive liquid and a surface that the droplet contacts. In **FIG. 2A**, a droplet **210** of conductive liquid is sandwiched between dielectric **202** and dielectric **204**. The dielectric can be, for example, tantalum oxide, or another dielectric material. An electrode **206** is buried within dielectric **202** and an electrode **208** is buried within dielectric **204**. The electrodes **206** and **208** are coupled to a voltage source **212**. In **FIG. 2A**, the system is electrically non-biased. Under this non-bias condition, the droplet **210** forms a contact angle, referred to as θ_1, with respect to the surface **205** of the dielectric **204** that is in contact with the droplet **210**. A similar contact angle exists between the droplet **210** and the surface **203** of the dielectric **202**.

[0031] **FIG. 2B** is a schematic diagram **230** illustrating the system **200** of **FIG. 2A** under an electrical bias. The voltage source **212** provides a bias voltage to the electrodes **206** and **208**. The voltage applied to the electrodes **206** and **208** creates an electric field through the conductive liquid droplet causing the droplet to move. The movement of the droplet **210** increases the capacitance of the system, thus increasing the energy of the system. In this example, the contact angle of the droplet **240** is altered with respect to the contact angle of the droplet **210**. The new contact angle is referred to as θ_2, and is a result of the electric field created between the electrodes **206** and **208** and the droplet **240**.

[0032] It is typically desirable to isolate the droplet from the electrodes, and thus allow the droplet to become part of a capacitive circuit. The application of an electrical bias as shown in **FIG. 2B**, makes the surface **205** of the dielectric **204** and the surface **205** of the dielectric **202** more wettable with respect to the droplet **240** than the no-bias condition shown in **FIG. 2A**. Although the surface tension of the liquid that forms the droplet **240** resists the electrowetting effect, the contact angle changes as a result of the creation of the electric field between the electrodes **206** and **208**. As will be described below, the change in the contact angle alters the curvature of the droplet and leads to translational movement of the droplet.

[0033] **FIG. 3A** is a schematic diagram illustrating an embodiment of an electrical switch **300** employing a conductive liquid droplet. The switch **300** includes a dielectric **302** having a surface **303** forming the floor of the switch, and a dielectric **304** having a surface **305** that forms the roof of the switch. A droplet **310** of a conductive liquid is sandwiched between the dielectric **302** and the dielectric **304**.

[0034] The dielectric **302** includes an electrode **306** and an electrode **312**. The dielectric **304** includes an electrode **308** and an electrode **314**. The electrodes **306** and **312** are buried within the dielectric **302** and the electrodes **308** and **314** are buried within the dielectric **304**. In this example, and to induce the droplet **310** to move toward the electrodes **312** and **314**, the electrodes **306** and **308** are coupled to an electrical return path **316** and are electrically isolated from electrodes **312** and **314**, and the electrodes **312** and **314** are coupled to a voltage source **326**. Alternatively, to induce the droplet **310** to move toward the electrodes **306** and **308**, the electrodes **312** and **314** can be coupled to an isolated electrical return path and the electrodes **306** and **308** can be coupled to a voltage source.

[0035] In this example, the switch **300** includes electrical contacts **318**, **322**, and **324** positioned on the surface **303** of the dielectric **302**. In this example, the contact **318** can be referred to as an input, and the contacts **322** and **324** can be referred to as outputs. As shown in **FIG. 3A**, the droplet **310** is in electrical contact with the input contact **318** and the output contact **322**. Further, in this example, the droplet **310** will always be in contact with the input contact **318**.

[0036] As shown in **FIG. 3A** as a cross section, the droplet **310** includes a first radius, r_1, and a second radius, r_2. When electrically unbiased, i.e., when there is zero voltage supplied by the voltage source **326**, the curvature of the radius r_1 equals the curvature of the radius r_2 and the droplet is at rest. The radius of curvature, r, of the droplet is defined as

$$r = \frac{d}{\cos\theta_{top} + \cos\theta_{bottom}} \qquad \text{Eq. 1}$$

where d is the distance between the surface **303** of the dielectric **302** and the surface **305** of the dielectric **304**, cos θ_{top} is the contact angle between the droplet **310** and the surface **305**, and cos θ_{bottom} is the contact angle between the droplet **310** and the surface **303**. Therefore, as shown in **FIG. 3A**, the droplet **310** is at rest whereby the radius r_1 equals the radius r_2, where the curvatures are in opposing directions

[0037] Upon application of an electrical potential via the voltage source **326**, a new contact angle between the droplet **310** and the surfaces **303** and **305** is defined. The following equation defines the new contact angle.

$$\cos\theta(V) = \cos\theta_o + \frac{\varepsilon}{2\gamma t}V^2 \qquad \text{Eq. 2}$$

[0038] Equation 2 is referred to as Young-Lipmann's Equation, where the new contact angle, cos θ(V), is determined as a function of the applied voltage. In equation 2, ε is the dielectric constant of the dielectrics **302** and **304**, γ is the surface tension of the liquid, t is the dielectric thickness, and V is the voltage applied to the electrode with respect to the conductive liquid. Therefore, to change the contact angle of the droplet **310** with respect to the surfaces **303** and **305** a voltage is applied to electrodes **314** and **312**, thus altering the profile of the droplet **310** so that r_1 is not equal to r_2. If r_1 is not equal to r_2, then the pressure, P, on the droplet **310** changes according to the following equation.

$$P = \gamma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \quad \text{Eq. 3}$$

[0039] **FIG. 3B** is a schematic diagram illustrating the movement imparted to a droplet of conductive liquid as a result of the pressure change of the droplet **310** caused by the reduction in contact angle due to electrowetting. When a voltage is applied to the electrodes **314** and **312** by the voltage source **326**, the contact angle of the droplet **310** with respect to the surfaces **303** and **305** in **FIG. 3A** is reduced so that r_1 does not equal r_2. When the radii r_1 and r_2 differ, a pressure differential is induced across the droplet, thus causing the droplet to translate across the surfaces **303** and **305**.

[0040] **FIG. 3C** is a schematic diagram **330** illustrating the switch **300** of **FIG. 3A** after the application of a voltage. As shown in **FIG. 3C**, the droplet **310** has moved and now electrically connects the input contact **318** and the output contact **324**. In this manner, electrowetting can be used to induce translational movement in a conductive liquid and can be used to switch electronic signals.

[0041] **FIG. 4A** is a schematic diagram illustrating a cross-section of a switch according to a first embodiment of the invention. In a switch **400**, a droplet **410** of a conductive liquid that contacts only one surface is referred to as a "sessile" droplet. The sessile droplet **410** rests on a surface **416** of a dielectric **402**. The dielectric can be, for example, tantalum oxide and the droplet **410** can be mercury, a gallium alloy, or another conductive liquid. An input contact **412**, referred to in this embodiment as radio frequency input (RF in) contact and an output contact **408**, RF out, are formed on the surface **416** of the dielectric **402**. The droplet **410** is in electrical contact with the input contact **412**. The surface **416** of the dielectric **402** is also at least partially covered with one or more features that influence the contact angle formed by the droplet **410** with respect to the surface **416**. Examples of features that influence the contact angle formed by the droplet **410** with respect to the surface **416** include the type of material that covers the surface **416**, the patterning of a wetting material formed over a non-wetting surface, and microtexturing to alter the wettability of portions of the surface **416**, etc. These features will be described below.

[0042] The dielectric **402** also includes an electrode **404** and an electrode **406** coupled to a voltage source **414**. The electrodes **404** and **406** are buried within the dielectric **402**. With no electrical bias, the droplet **410** conforms to a prespecified shape that can be determined by controlling the contact angle between the surface **416** and the droplet **410**, as mentioned above. While the droplet **410** is located over the electrodes **404** and **406**, it should be understood that the term "over" is meant to describe a spatially invariant relative relationship between the droplet **410** and the electrodes **404** and **406**. Moreover, the droplet **410** is located proximate to the electrodes **404** and **406** so that if the switch **400** were inverted, the droplet **410** would still be proximate to the electrodes **404** and **406** as shown. Further, the relationship between the droplet and the electrodes in the embodiments to follow is similarly spatially invariant.

[0043] **FIG. 4B** is a schematic diagram illustrating the switch **400** of **FIG. 4A** under an electrical bias. In **FIG. 4B**, an electrical bias is applied by the voltage source **414** to the electrodes **404** and **406**. The electrical bias establishes an electric field that passes through the droplet **410**, thus causing the droplet **410** to deform as shown in **FIG. 4B**. The applied bias alters the contact angle between the droplet **410** and the surface **416**, thus causing the droplet to flatten and overlap both contacts **412** and **408**. In this manner, a simple switch is formed that uses electrowetting of the droplet **410** to make and break electrical contact between the input contact **412** and the output contact **408**.

[0044] When an electrical bias is applied to the electrodes **404** and **406**, the droplet completes a capacitive circuit between the electrodes **404** and **406** and if the dielectric is of constant thickness, the applied voltage is evenly distributed causing the same change in contact angle of the droplet **410** over both electrodes **404** and **406**. In this example, when the bias is removed, the droplet **410** will return to its original state as shown in **FIG. 4A**, and break contact with the output electrode **408**. The embodiment shown in **FIGS. 4A and 4B** is referred to as a "non-latching" switch in that the droplet returns to its original state when the bias voltage is removed, thus breaking electrical contact between the input contact **412** and the output contact **408**.

[0045] **FIG. 4C** is a plan view **460** illustrating the switch shown in **FIGS. 4A and 4B**. The droplet **410** under no electrical bias is shown in contact only with the input contact **412**, while the droplet **440**, which is under an electrical bias, is shown in contact with the input contact **412** and the output contact **408**.

[0046] **FIG. 4D** is a plan view **480** illustrating the surface **416** of the dielectric **402** including a feature that alters the wettability of the surface with respect to the droplet. In this example, the surface **416** of the dielectric **402** is silicon dioxide (SiO_2) to which strips of a wetting material **482** have been applied to alter the initial contact angle between the droplet **410** and the surface **416**, thus forming an intermediate contact angle for the droplet **410**. In this example, the wetting material **482** is gold (Au). Alternatively, wetting materials other than gold can be applied, forming other contact angles between the surface **416** and the droplet **410**. Further, microtexturing, which is the formation of small trenches in the surface **416** can also be applied to alter the contact angle between the surface **416** and the droplet **410**. In this manner, an initial contact angle can be established between the surface **416** and the droplet **410**. By defining an initial contact angle, the contact angle change due to the application of an electrical bias can be closely controlled, thereby allowing control over the switching function.

[0047] **FIG. 5A** is a plan view illustrating a second embodiment **500** of a switch according to the invention. **FIG. 5A** shows a switch **500** including a sessile droplet **510** residing on the surface **504** of a dielectric **502**. Electrodes **506**, **508**, **512** and **514** are formed below the surface **504** of the dielectric **502**. The droplet **510** is shown in a first position **510*a*** in contact with an input contact **518** and with an output contact **522**, and is shown in a second position **510*b*** in contact with the input contact **518** and the output contact **524**.

[0048] The electrode **508** is coupled via connection **532** to electrical return path **516** and the electrode **506** is connected via connection **536** to electrical return path **516**. The electrodes **512** and **514** are coupled via connection **538** and **534** to voltage source **526** and are electrically isolated from electrodes **506** and **508**. In this embodiment, when electrically biased, the electrical connections will induce the droplet to move toward the electrodes **512** and **514**. Alternatively, to induce the droplet to move toward the electrodes **506** and **508**, the electrodes **512** and **514** can be coupled to the electrical return path **516** and the electrodes **506** and **508** can be coupled to a voltage source.

[0049] Upon the application of a bias voltage, the sessile droplet **510** will translate from the position shown as **510***a* to the position shown as **510***b*. This embodiment is referred to as a "latching" embodiment in that the position of the droplet **510** remains fixed until a bias voltage is applied to cause the droplet to translate. In this example, by controlling the voltage applied to electrodes **512** and **514** and electrodes **506** and **508**, the droplet **510** is toggled to provide a switching function. With no electrical bias applied, the droplet **510** is confined to a specific area, shown in outline as **510***a*, by tailoring an initial contact angle between the droplet and the surface **504**. By selecting the material of the droplet **510** and the material applied over the surface **504** to define the wettability between the droplet **510** and the surface **504**, it is possible to tailor the initial contact angle to ensure latching of the droplet **510**.

[0050] **FIG. 5B** is a cross-sectional view illustrating the switch **500** of **FIG. 5A**. The switch **500** includes a droplet **510** resting on the surface **504** of the dielectric **502**. Depending upon the bias voltage applied by the voltage source **526** to the electrodes **512** and **514**, the droplet **510** will translate between position **510***a* and **510***b*, thus switching a signal from the input contact **518** to either the output contact **522** or the output contact **524**.

[0051] **FIG. 6A** is an alternative embodiment **600** of the switch **500** shown in **FIG. 5A**. In **FIG. 6A**, the electrodes **606** and **612** include interleaved contacts, and the electrodes **608** and **614** include interleaved contacts, collectively referred to at **620**. The application of a bias voltage from the voltage source **626** causes the droplet **610** to translate from position **610***a* to position **610***b*, thus causing an input signal applied to input contact **618** to be directed either to output contact **622** or to output contact **624**, depending on the position of the droplet **610**.

[0052] **FIG. 6B** is a cross-sectional view illustrating the switch **600** of **FIG. 6A**. By controlling the voltage applied to electrodes **612** and **614** and electrodes **606** and **608** the droplet **610** will translate between positions **610***a* and **610***b*, thus causing an input signal applied to input contact **618** to be directed either towards output contact **622** or output contact **624**, depending on the position of the droplet **610**.

[0053] **FIG. 7** is a schematic diagram **700** illustrating another alternative embodiment of a switch according to the invention. The switch **700** illustrates what is referred to as a "fully constrained" configuration in that a droplet **710** is constrained between a dielectric **702** having a surface **703**, a dielectric **704** having a surface **705**, and a microfluidic boundary **720** between the dielectric **702** and the dielectric **704**. The microfluidic boundary forms a cavity to contain the droplet **710**. While the microfluidic boundary **720** is illustrated as a separate element in **FIG. 7**, the microfluidic boundary **720** may be incorporated into a structure including the dielectric **704** and/or the dielectric **702**.

[0054] The dielectric **702** includes an electrode arrangement similar to the electrode arrangement shown in **FIGS. 5A, 5B** or **FIGS. 6A and 6B**. However, only electrodes **706** and **712** are shown in **FIG. 7**.

[0055] A bias voltage applied from voltage source **726** causes the droplet **710** to translate between position **710***a* and **710***b*, thus creating a switching function. In this embodiment, upon the application of a bias voltage, the contact angle between the droplet **710** and the surface **703** will change, leading to translation of the droplet across the surfaces **703** and **705**.

[0056] **FIG. 8** is a schematic diagram **800** illustrating an alternative embodiment of the switch **700** shown in **FIG. 7**. In **FIG. 8**, the dielectric **804** includes electrodes **808** and **814**. The electrodes **808** and **814** can be arranged as described in **FIGS. 5A and 5B**, or can be interleaved as described above in **FIGS. 6A and 6B**. The surface **803**, the surface **805** and a microfluidic boundary **820** form a cavity that constrains the droplet so that it may translate between positions **810***a* and **810***b* upon application of a bias voltage from voltage source **826**. In this embodiment, upon the application of a bias voltage, the contact angle between the droplet **810** and the surfaces **803** and **805** will change, leading to translation of the droplet across the surfaces **803** and **805**.

[0057] **FIG. 9** is a schematic diagram **900** illustrating surface texturing that can be applied to any of the switches described herein. The surface texturing described in **FIG. 9** can be applied to any of the embodiments of the switch described above to alter the initial contact angle between a droplet and a surface with which the droplet is in contact. The dielectric **902** includes a non-wetting pattern **904** applied approximately as shown, thus leaving a wetting pattern **906** over which the droplet will reside. In addition, the wetting pattern **906** can be further defined to include non-wetting portions **912** to finely tailor an initial contact angle between the droplet and the surface with which the droplet is in contact. In this manner, the initial contact angle can be tailored to suit particular applications.

[0058] **FIG. 10** is a schematic diagram **1000** illustrating an exemplary dielectric substrate that may form the lower surface, or floor, of a switch described above. In this example, a silicon substrate **1002** includes a patterning of metal thin film material shown generally as locations indicated at **1006** over the surface **1004** that forms a floor. In this example, the dielectric film that would be applied over the metal film is omitted for clarity. An approximate location of the droplet is shown at **1010**. The input contact is shown at **1012** and the output contacts are shown at **1014** and **1016**.

[0059] **FIG. 11** is a perspective view **1100** illustrating a cap **1102** that forms the roof and microfluidic chamber of a switch of **FIG. 7, 8** or **9**. In this example, the cap **1102** can be fabricated from, for example, a glass material such as Pyrex®, the underside **1104** of which is shown in **FIG. 11**. The cap **1102** includes a roof portion **1120** and a wall portion **1125** that forms the microfluidic boundary described above. Portions of a metal thin film illustrated at **1106** can be selectively applied to the surface **1104** to correspond at least partially with the portions **1006** of **FIG. 10** so that the cap **1102** can be bonded to the substrate **1002** shown in **FIG. 10**. For example, in places where the metal thin film **1006** of **FIG. 10** contacts the metal thin film **1106** of **FIG. 11**, a thermal compression bond using heat and pressure can be achieved, thus forming a structure that can encapsulate a droplet. Alternatively, anodic bonding can be used to bond the substrate **1002** (**FIG. 10**) to the cap **1102**. In this manner, a microfluidic chamber can be formed within which the droplet described above may reside. Electrodes may be embedded into or applied to the roof portion **1120**.

[**0060**] The wall **1125** of the cap **1102** can also include one or more features to alter wetting and latching ability of a switch. Such a feature is generally shown at **1130** and can be, for example, openings that might be vented to a reference reservoir (not shown). The openings **1130** can be formed by etching down from the surface **1104** toward the surface of the roof portion **1120** as indicated by the opening indicated for reference at **1131**. The other openings **1130** can be formed similarly. When the openings **1130** are sufficiently small, the liquid metal will not wick through, provided the walls are relatively non-wetting, but will remain in the chamber formed by the roof portion **1120**, the wall **1125** and the floor surface **1004** (**FIG. 10**). The adhesion energy between the droplet and the wall **1125** will be reduced by the openings **1130**. Selectively defining the openings **1130** to control the adhesion energy can control the latching strength of the switch. The cap **1102** also includes a fill port **1114**, through which the conductive liquid may be introduced, and vent ports **1108** and **1112**.

[**0061**] **FIG. 12** is a flowchart **1200** describing a method of forming a switch according to an embodiment of the invention. In block **1202** a substrate including buried electrodes is provided. In block **1204** a droplet of conductive liquid is provided over the substrate. In block **1206**, a power source configured to create an electric circuit including the droplet of conductive liquid is provided. In block **1208** a feature is formed on the surface. The feature determines an initial contact angle between the surface and the droplet.

[**0062**] This disclosure describes the invention in detail using illustrative embodiments. However, it is to be understood that the invention defined by the appended claims is not limited to the precise embodiments described.

We claim:

1. An electronic switch, comprising:

a substrate having a surface and an embedded electrode;

a droplet of conductive liquid located over the embedded electrode;

a power source configured to create an electric circuit including the droplet of conductive liquid; and

a feature on the surface, wherein the feature determines an initial contact angle between the surface and the droplet.

2. The electronic switch of claim 1, in which the feature further comprises a wetting material patterned over a non-wetting material.

3. The electronic switch of claim 1, in which the feature is created using microtexturing to make a predefined region less wetting.

4. The electronic switch of claim 1, further comprising a cap over the droplet, the cap configured to form a fluidic boundary to confine the droplet.

5. The electronic switch of claim 4, in which the cap further comprises an embedded electrode.

6. The electronic switch of claim 4, in which the cap further comprises a feature to alter the wettability of the droplet with respect to a surface of the fluidic boundary.

7. The electronic switch of claim 6, in which the switch is a two position switch and the droplet latches.

8. A method for making an electronic switch, comprising:

providing a substrate having a surface and an embedded electrode;

providing a droplet of conductive liquid over the embedded electrode;

providing a power source configured to create an electric circuit including the droplet of conductive liquid; and

forming a feature on the surface wherein the feature determines a contact angle between the surface and the droplet.

9. The method of claim 8, further comprising defining the contact angle by patterning a wetting material on a non-wetting material to form an intermediate contact angle.

10. The method of claim 8, further comprising microtexturing the surface to make a predefined region less wetting.

11. The method of claim 8, further comprising forming a cap over the droplet, the cap configured to form a fluidic boundary to confine the droplet.

12. The method of claim 11, further comprising forming embedded electrodes in the cap.

13. The method of claim 11, further comprising forming a feature in the cap, the feature configured to alter the wettability of the droplet with respect to a surface of the fluidic boundary.

14. The method of claim 13, in which the switch is a two position switch and the droplet latches.

15. An electronic switch, comprising:

a substrate having a surface and an embedded electrode;

a droplet of conductive liquid located over the embedded electrode;

a cap over the droplet, the cap configured to form a fluidic boundary to confine the droplet, the cap including an embedded electrode;

a power source configured to create an electric circuit including the droplet of conductive liquid; and

a feature on the surface, wherein the feature determines an initial contact angle between the surface and the droplet, and wherein a surface of the fluidic boundary comprises a feature that alters the wettability of the droplet with respect to the surface of the fluidic boundary.

16. The electronic switch of claim 15, in which the feature further comprises a wetting material patterned over a non-wetting material.

17. The electronic switch of claim 15, in which the feature is created using microtexturing to make a predefined region less wetting.

18. The electronic switch of claim 15, in which the switch is a two position switch and the droplet latches.

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